Effects of nonuniformity in thin-film photovoltaics

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We discuss the physical origin and effects of micrononuniformities on thin-film photovoltaics. The key factors are the large device area and the presence of potential barriers in the grain boundaries (for polycrystalline films) and in device junctions. We model the nonuniformity effects in the terms of random microdiodes connected in parallel through a resistive electrode. The microdiodes of low open circuit voltages are shown to affect macroscopically large regions. They strongly reduce the device performance and induce its nonuniform degradation in several different modes. We support our predictions by experiments, which show that the device degradation is driven by the light-induced forward bias and is spatially nonuniform.
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Recent advances in large area thin-film device manufacturing raise a number of physical problems related to the issue of lateral uniformity. Several basic facts underlie that issue. (i) The larger the device area, the harder to maintain thin-film uniformity during the deposition and subsequent treatments. (ii) In polycrystalline films the very nature of polycrystallinity undermines the device lateral uniformity, for variability in the grain sizes and related physical parameters are not averaged out in a system in which the film thickness is comparable to the grain size. (iii) The grains constituting polycrystalline material are intrinsically nonuniform: grain boundaries differ considerably from the core region. This results in potential barriers (to either electrons or holes) associated with the grain boundaries. (iv) Side by side with those of the grain boundaries, there are other potential barriers, such as those caused by the metal–semiconductor junction in the electric contact and/or band structure discontinuity at the metallurgical junction of two different semiconductors. Electronic transport through the potential barriers is exponentially sensitive to the local parameter fluctuations in both the temperature activated and tunneling modes. (v) Because, in general, the photovoltaic device physics is that of a diode, and because the diode I/V characteristic is exponential, the device can be exponentially sensitive to small variations in the local film parameters.

Experimentally, lateral nonuniformities manifest themselves in spatial variations of the device local characteristics and in the variability of the measured parameters between nominally identical devices.[1] These may include the standard diode parameters, open circuit voltage (V_{oc}), efficiency, and some degradation parameters. The nonuniformities are seen in the device mappings, such as photoluminescence mapping,[2] V_{oc} mappings,[3] optical beam induced current (OBIC) mappings,[4] electron beam induced current mappings,[5] liberated Joule heat mappings,[3] and, quite recently, in the electroluminescence mappings,[6] the latter having shown also a nonuniform degradation. An interesting case of nonuniform degradation was explored by OBIC techniques[7] where it was found that one originally bad microscopic spot drove the entire device degradation, while the surrounding areas showed rather stable behavior. The above-mentioned mappings have revealed a variety of fluctuation length scales (ℓ) ranging from microns to tenths of a millimeter.

To some extent, the notion of a thin-film device being laterally nonuniform has been known since study of transverse hopping conductivity of amorphous films[8] and nonuniform barriers in semiconductor structures (see Ref. 9 for a review and Refs. 10 and 11 for more recent sources). One general trend established in the above-mentioned work was that if the transverse conductivity depends on the local parameters exponentially (as occurs with tunneling or activation), then gigantic lateral nonuniformities take place. The underlying physics is that the exponential dependence makes some local configurations especially effective pathways. In spite of their low concentration, they consume almost the entire current and are characterized by an exponentially broad parameter distribution.

Our model is aimed at accounting for the specificity of the lateral fluctuations in thin-film photovoltaics, which lies in the device diode nature and in the presence of a resistive electrode. This is reflected in the equivalent circuit of Fig. 1, in which the microdiodes constituting the device are different. The characteristic size of a microdiode is of the order of the micrononuniformity length scale ℓ.

Based on the available data,[3] one can estimate the dispersion δV_{oc} in the microdiode V_{oc} to exceed the characteristic thermal voltage kT/e. Hence, microdiode currents,

$$j = j_0 \left\{ \exp\left[\frac{e(V - V_{oc})}{kT} \right] - 1 \right\}, \tag{1}$$

are exponentially different. This is illustrated in Fig. 2, where the two diodes in parallel represent a weak element (small

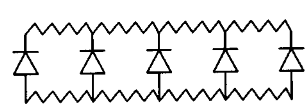

FIG. 1. The equivalent circuit of random microdiodes representing a laterally nonuniform device.

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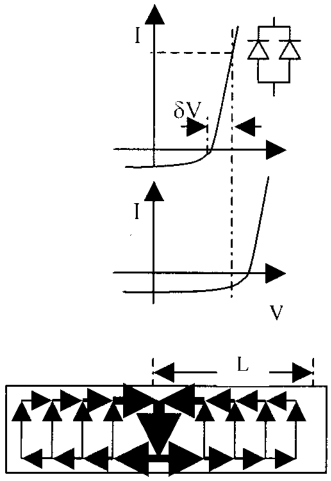

FIG. 2. *I/V* curves of a weak diode and its more robust neighborhood, and corresponding electric currents shunted through the weak diode (large vertical arrow).

V_{oc} diode) and its more robust neighbors (large V_{oc} diode). The weak diode finds itself under considerable forward bias δV and correspondingly strong current

$$j_w \approx j_0 \exp(e\,\delta V/kT), \tag{2}$$

which is supplied by more robust diodes. The latter are restricted to the surrounding region of the screening length[12]

$$L = \sqrt{\delta V/\rho j_0}, \tag{3}$$

where ρ is the electrode sheet resistance, and j_0 is understood as the diode-specific (per area) current. The physical meaning of the length L is that the electric potential fluctuation δV is supported by the resistive potential drop $I\rho$, where the electric current $I = j_0 L^2$.

Associated with the typical device parameters (say, $\delta V \sim \delta V_{oc} \sim 0.05 \div 0.1$ eV, $\rho \sim 10\ \Omega/\Box$, and $j_0 \sim 0.1$ A/cm^2) is a macroscopically large $L \sim 1$ cm, which results in the inequality $L \gg \ell$. Hence, a weak microdiode plays the role of a shunt, robbing currents from a large number

$$N = \frac{j_w}{j_0} = \left(\frac{L}{\ell}\right)^2 \gg 1 \tag{4}$$

of its more robust neighbors in a microscopically large area of L^2 (see Fig. 2), and thus significantly lowering the device efficiency.[13]

One other immediate consequence of the above model is that the originally weak microdiodes may deteriorate still more, thus causing strongly nonuniform degradation in the system. Indeed, the electric current localization in a weak microdiode is accompanied by a corresponding increase in the charge carrier concentration and Joule heat. This may result in the local degradation occurring by such mechanisms as (i) electromigration of impurity ions[14] caused by the local variation in the electric field in a weak diode; (ii) accelerated defect creation by excessive local carrier concentration;[5] (iii) local corrosion (or other surface damage) induced by ions from ambient attracted to the excessive electric charges in the weak microdiode ends; (iv) direct action of locally increased current or heat; and (v) combinations of the above mechanisms.

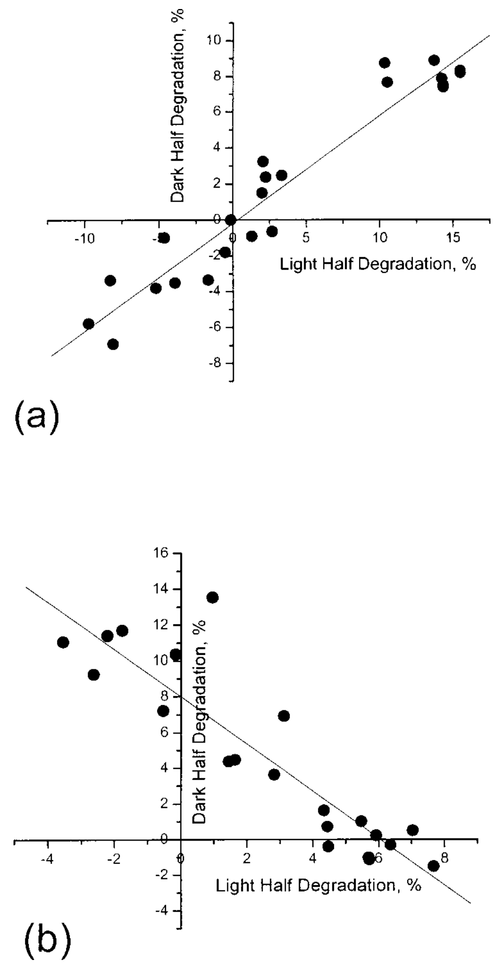

FIG. 3. (a) Relative open circuit voltage, V_{oc} and (b) short circuit current density, J_{sc} degradation in the light and dark halves of the electrically connected dot cells. Solid lines represent linear fits. Negative values correspond to cell improvement.

As an example, the charge carrier driven degradation kinetics is readily formalized by assuming that the defect generation rate is proportional to the local nonequilibrium carrier concentration,[5] the latter being exponentially dependent on the bias $\delta V = V_{oc} - \langle V_{oc} \rangle$, where V_{oc} is linear in the defect concentration. This results in

$$V_{oc}(t) = V_{oc}(0) + kT\ln(1 - t/\tau),$$
$$\tau \propto \exp(eV_{oc}(0)/kT). \tag{5}$$

Hence, the lower the V_{oc}, the exponentially faster the degradation, and a moderate dispersion in local V_{oc} results in exponentially broad dispersion in local degradation times.

Crucial to the above reasoning of progressively degrading weak diodes was the assumption of an effect caused by the electrical bias. The following experiments were designed to verify the role of electrical bias in device degradation. In a set of roundish CdTe/CdS dot cells,[15] each cell was half shadowed along its diameter. After one month light soak, the screens were removed and the devices were scribed along their diameters, to make the former dark and light parts electrically disconnected. We have intentionally chosen devices with a broad range of deposition parameters, some of them degraded, others improved under limited time exposure. As a control we light soaked a number of fully open cells.

The data shown in Fig. 3 reveal that there was no preference of the light over the dark halves in the amount of degradation. This is consistent with the dark half screening radius $L > 1$ cm, estimated from Eq. (3) with the dark current density $j_0 < 0.1$ A/cm^2 and δV equal to the difference between the open and shadowed half V_{oc}. Such a long screening length implies that the bias has spread over the entire cell. Therefore this is not the light per se, but rather its generated forward electrical bias which is responsible for the device degradation.

In addition, Fig. 3(b) shows that, to the first approximation, the sum of the light and dark halves J_{sc} degradation is constant ($\sim$6%–8%). The latter turns out to be approximately a factor of two larger than that of our control fully open cells ($\sim$3%–4%). This difference can be understood if J_{sc} degradation is significantly nonuniform and occurs in either half of the cell. Small current density degradation in the control cells is then explained by mistakenly relating the current degradation to the area that is overestimated (whole cell instead of half of a cell). We conclude that the above experiments are fully consistent with our model.

While the above argument partially referred to the issue of polycrystallinity, and the experiments were restricted to a polycrystalline device, we believe that similar phenomena can occur in amorphous thin film devices based on *a*-Si:H, in which microononuniformities have different physical origin. Indeed, some empirical relations between structural inhomogeneities and the amount of light-induced degradation in *a*-Si:H were observed,[16] as well as the development of nonuniformities in the course of light-soaking.[17]

A comment is in order regarding the philosophy of nonuniform degradation presented in this paper. It is customary for nature to concentrate stress on nonuniformities as different objects deteriorate, e.g., mechanical breakdown caused by the stress concentration on dislocations or other material imperfections, electrical breakdown through the current filaments in electrically weak regions, and dendrite growth preceding electric capacitor failure. Even biological breakdown occurs through a disease hitting the weakest, most vulnerable part in a body.

The nonuniform degradation has so far remained overlooked in photovoltaics. We believe that understanding effects of nonuniformities will help to improve thin-film photovoltaics performance and stability.

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